EXDEP/CTX
AN EXPLOSIVE DETECTION SYSTEM FOR SCREENING LUGGAGE WITH HIGH ENERGY X-RAYS

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ABSTRACT

TITAN has developed a new technique for detecting explosives using an RF LINAC. The patented EXDEP technique uses an intense 14-MeV x-ray beam to photoactivate the nitrogen comprising >18.5% of most explosives. Activated nitrogen ($t_{1/2}$ = 10 minutes) decays emitting a positron, which annihilates producing two 511-keV photons that are detected. An EXDEP/CTX system has been designed to screen luggage for concealed explosives by identifying their unique combination of chemical constituents and physical density. The EXDEP technique measures the nitrogen concentration of materials on a per-unit-volume basis together with a three-dimensional computer tomography x-ray (CTX) scanner to measure their physical density. The determination of whether or not there is an explosive present is based upon two factors: (1) the count rate for each volume element and (2) the number of volume elements that have the appropriate count rate. The probability of detection for the EXDEP/CTX system should be over 99% with a false alarm probability substantially less than 1%.

EXPLOSIVE DETECTION SYSTEM

Explosives can be identified by their unique combination of chemical constituents and physical density. Explosives which have been used by terrorists have nitrogen densities between 0.15 and 0.60 g/cm^3 and physical densities between 1.2 and 1.8 g/cm^3. Figure 1 compares the characteristics of bulk explosives with common plastics and other high-nitrogen concentration materials. We have surveyed most common materials including foodstuffs, fabrics, plastics, organic compounds, and drugs. The only items that have similar densities and high nitrogen concentrations are polyurethane and melmac. Identification of bulk explosives, therefore, requires a technique to measure the nitrogen concentration and the physical density.

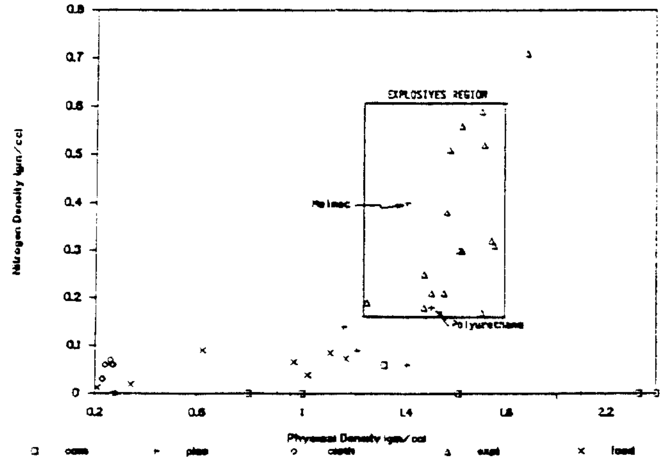

Figure 1. Plot of physical density vs nitrogen density.

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The configuration proposed for the explosive detection system is shown in Figure 2. The baggage to be inspected is placed on a conveyor, which carries it past the three components of the explosive detection system. The first component of the system is the EXDEP high-energy x-ray machine, similar to a cancer therapy device, which illuminates the luggage. Certain materials within the luggage, including the explosives, are slightly activated. The second component is a sensitive detector array that provides a three-dimensional image of the activity concentration of the materials. The detector array is separate and independent of the illumination and may be located far from the illumination source. In fact, multiple detector stations can accommodate one illumination station. Finally, the third component is the CTX system which maps in three dimensions the physical density of those areas with appropriate activity concentrations. By overlapping the two images, items with both physical density and activity concentrations appropriate for explosives are identified.

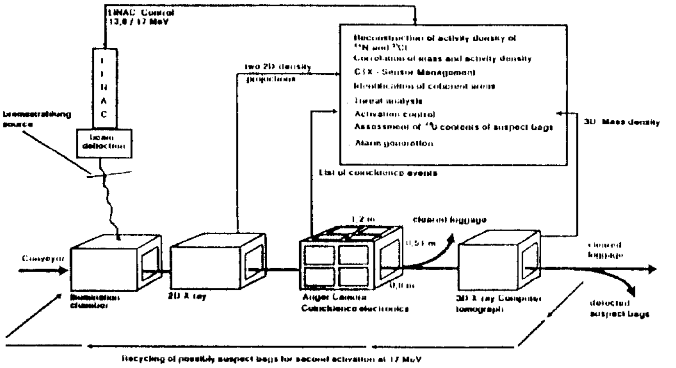


Figure 2. Explosives detection system using EXDEP.

EXDEP CONCEPT

The EXDEP concept is shown schematically in Figure 3. A radio frequency linear accelerator (RF LINAC) is used to produce an electron beam with an energy of 13.5 MeV. The electrons strike a tantalum or tungsten target and produce bremsstrahlung radiation with a maximum energy equal to the electron beam energy. The x-rays interact with the explosive and activate the nitrogen via the photoneutron (γ,n) reaction. The stable nitrogen isotope ^{14}N thus becomes the radioactive isotope ^{13}N, which then decays with a 10-minute half-life via positron emission to ^{13}C. The positron immediately slows down and annihilates, producing two 511-keV photons. These photons are easily detected and counted in coincidence using scintillation detectors.

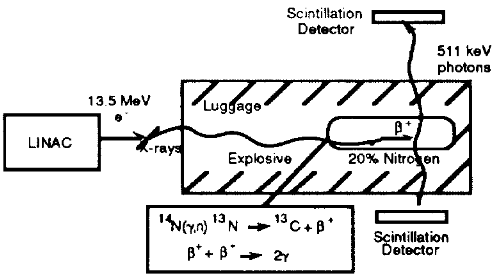


Figure 3. EXDEP concept.

The relatively low nitrogen photonuclear activation threshold energy at 10.6 MeV and the subsequent ten minute half-life positron decay is almost a unique combination. Most other elements common in luggage have photonuclear reaction thresholds above 13 MeV, produce no positron, or have very short or very long half-lives. Those few elements which do react similarly to nitrogen, and thus could contaminate the nitrogen signal, are potentially hazardous materials and are not typically found in luggage.

The limited number of isotopes which are detectable by the EXDEP technique are shown in Table 1. The rare earths (praseodymium, samarium, and erbium) are not present in any significant amount in luggage. The metals (nickel, copper, zinc, gallium, zirconium, molybdenum, and silver) have mass densities which distinguish them from nitrogen. Moreover, the reaction cross section, density, and half-lives of these metals make the activity concentration significantly higher than that for nitrogen. Fluorine is found in trace amounts except for the compound teflon, which has a density of 2.2 g/cm^3. Phosphorus, chlorine, and bromine are elements which would not be expected in luggage and, if found, should indeed be identified as potentially hazardous.

Table 1. Isotopes Detectable by EXDEP.

Isotope	%	Thresh-old (MeV)	Cross Section (mb) at 13 MeV	Half-Life	% β+	$E_{max}\beta^+$ (MeV)
Nitrogen (^{14}N)	99.6	10.6	1	10 m	100	1.198
Fluorine (^{19}F)	100	10.4	2	110 m	97	0.635
Phosphorus (^{31}P)	100	12.3	<1	2.6 m	99	3.24
Chlorine (^{35}Cl)	75.8	12.8	2	32.3 m	50	2.5
Nickel (^{58}Ni)	68.3	12.2	5	36 hr	50	0.85
Copper (^{63}Cu)	69.2	10.9	20	9.8 m	97	2.93
Zinc (^{64}Zn)	48.6	11.9	10	38 m	92	2.34
Gallium (^{69}Ga)	60.1	10.3	30	68 m	87	1.9
Bromine (^{79}Br)	50.7	10.7	?	6.5 m	92	2.5
Zirconium (^{90}Zr)	51.4	12.0	25	78 hr	22	0.9
Molybdenum (^{92}Mo)	14.8	12.7	20	15.5 m	94	3.4
Silver (^{107}Ag)	51.8	9.5	75	24 m	60	1.96
Praseodymium (^{141}Pr)	100	9.4	150	3.4 m	50	2.37
Samarium (^{144}Sm)	3.1	10.5	250	8.9 m	50	2.47

The activity concentrations that are expected from various benign items containing those isotopes identified as EXDEP detectable are at least an order of magnitude higher than the TNT, except for bulk nylon which has an activity concentration that is only about half that of the explosives. Figure 4 shows schematically, for example, that the higher activity concentration from coins produces a higher count rate per volume element than explosives.

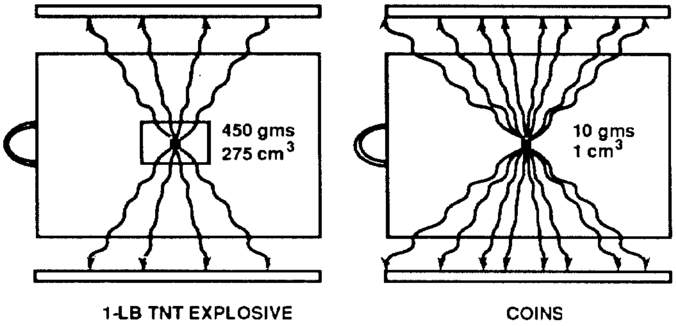


Figure 4. Different activity concentrations for explosive and coins.

A major advantage for EXDEP is the resolution achievable with a very efficient detector system. The improved resolution directly reduces the false-alarm rate. With low resolution (1000 cm^3), only an average nitrogen concentration in a given volume is measured. With high resolution (1 cm^3), the nitrogen concentration of individual items are measured over a small enough volume to distinguish explosives from most other nitrogenous materials.

In EXDEP two oppositely-directed, coincident, low-energy photons are counted simultaneously. The explosive lies on the line between the two detectors measuring the event. For multiple events, there are multiple lines that intersect at the explosive's location, as shown in Figure 4. The positron range (the distance that a positron travels before annihilation), Compton scattering of the annihilation photons before exiting the baggage, and uncertainty in the location of the photon interaction within the detector crystal blur the image somewhat, but the resolution still remains about one centimeter.

We have calculated the activity generated in the luggage from the direct bremsstrahlung radiation. Most contents of checked luggage, including food, clothing, plastics, and drugs, whose primary elements are carbon, hydrogen, and oxygen, will acquire no activity. For an example of residual activity, consider luggage with a 1-kg TNT explosive, 25 g of copper, 10 pennies, or 16 g of sterling silver. Irradiation with photons from a 1-mA electron beam per 0.3 m^2 of x-ray coverage produces less than 1 µCi of activity, which is equivalent to a dose of 0.0004 mR/hr.

EXPERIMENTAL DATA

We have conducted experiments which were sponsored jointly by Sandia National Laboratories (SNL) and the Defense Advanced Research Projects Agency (DARPA) to show that the EXDEP technique is effective at detecting concealed explosives. Melamine (~67% nitrogen by weight) was used to simulate TNT explosive, for safety reasons. The mock explosives were buried a few inches deep in sand or soil, which provided for attenuation of the 13.5 and 0.511 MeV photons.

The mock explosive targets were mounted on a carriage assembly which was stationary in the beam during irradiation, then moved down the track and in front of the BGO scintillation detectors. Single-channel-analyzer data, with the window set for the 511-keV photopeak, were taken to count the annihilation photons. Figure 5 shows a typical multichannel-analyzer spectrum of the mock explosive; the 511-keV photopeak stands clearly above the background photons from other decay processes. Figure 6 shows the number of counts verses time for a 1.5-kg TNT mock explosive buried at several different soil depths.The mock explosive is detectable for many minutes after illumination.

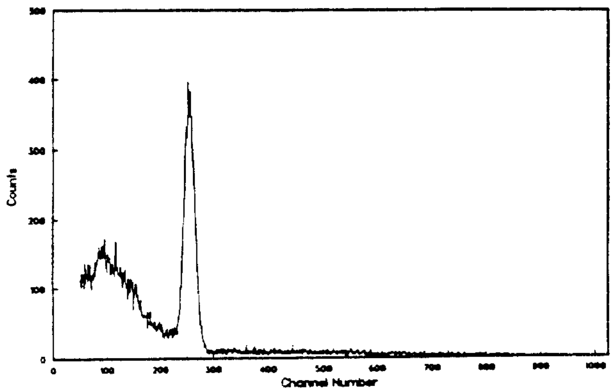


Figure 5. Multichannel analyzer spectrum showing 511-keV peak.

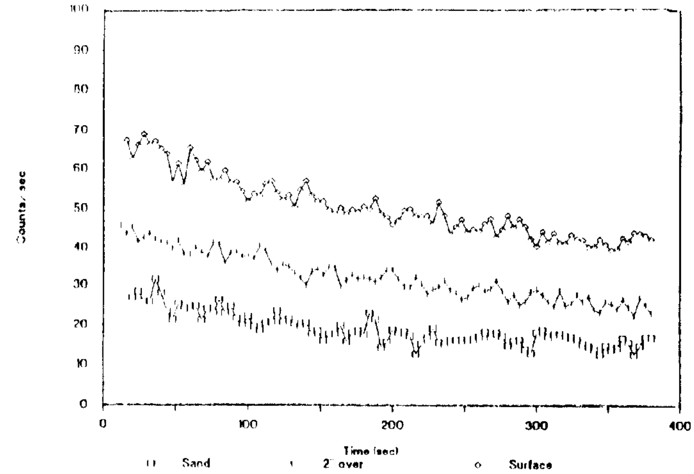


Figure 6. Number of counts vs time for a 1.5 kg TNT mock explosive.

We did an experiment using a PET camera at the University of Pennsylvania Medical Center to examine the resolution for very low count rates. We used 0.1-µCi ^{22}Na point sources and a solution of ^{68}Ga in water to simulate the activity from the illuminated explosive. The raw count data from the UGM PET camera is stored in a sinograph format for each two-dimensional slice through the object, each slice being 8 mm thick.

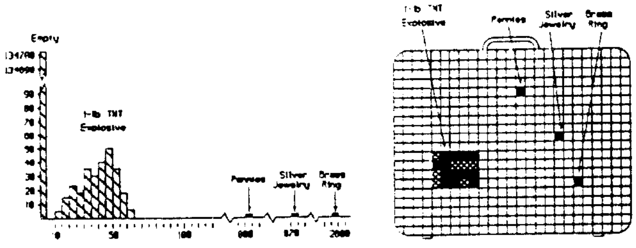
Figure 7 shows two sinograph slices through the volume containing three 0.1-µCi point sources placed 2 inches apart. The data was collected for a 20-sec count time. The picture clearly shows that a 0.1-µCi point source is observable and that the three are easily resolved. Similar sinographs for a 0.1-µCi point source immersed within a water solution containing 1.7 µCi of ^{68}Ga show the 0.1-µCi point source is visible in the distributed activity. The count time was 20 seconds, which is equivalent to counting a 2.3 x 10^{-3} µCi/cm^3 source for a 6-sec count time. These experimental results clearly demonstrate that the activity levels which we expect to produce using the EXDEP accelerator are observable using a PET camera. Moreover, the linear resolution that is achievable is ~1 cm.

Figure 7. Sinograph of three 0.1-µCi point sources 2 inches apart.

CONCLUSION

There is an explosive only if a sufficient number of cells have the correct count rate. Consider a 30 cm x 60 cm x 75 cm piece of luggage, which would be imaged into 135000 individual cubic centimeter cells. From our model calculations, a TNT explosive would produce 20 counts in a 10-sec count interval if there were 50% attenuation for each annihilation photon. A 1-lb piece of TNT would occupy 275 cells. Ten pennies in a cell would produce almost 800 counts in the same time interval with 50% attenuation. The background count rate per cell is less than 1 count per 10 sec. For a suitcase with pennies, a brass ring, a piece of sterling silver jewelry, and 1-lb TNT explosive, a histogram of the counts might look like Figure 8a. A two-dimensional slice through the bag may look like Figure 8b, where the gray scales correspond to the counts. Either representation clearly shows the presence of the explosive.

The CTX post-scanning instrument would produce similar images with density information. The superposition of the two images would identify an explosive uniquely.



(a) (b)

Figure 8. (a) Histogram and (b) Image from EXDEP screening.